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MECHANICS DIVISION

TECHNICAL NOTE

Number SB/Ap-19
Date 23 March 1948
SB Proj. No. 11.1

ON THE DEFINITION OF "HYPERSONIC" FLOW

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On The Definition of "Hypersonic" Flow

1. No universal agreement as to the definition of the expression "hypersonic" has yet been reached. The present MTN does not add a new definition. Rather, it is intended to present briefly the definitions known to the author and to discuss some of their physical implications. It will also be stated which terminology is in present use at NOL in connection with project SB 11.1, the "Experimental Investigation of Hypersonic Flow". References are given at the end of the MTN.

2. H. S. Tsien states in (Ref. 1): "Hypersonic flows are flow fields where the fluid velocity is much larger than the velocity of propagation of small disturbances, the velocity of sound." In such flow fields the application of the linearized theory is not possible, (as is also true in the transonic case) because its underlying physical assumptions cannot be made. It should be remembered that in order to apply the linearized treatment, it is required that the perturbation velocity due to the presence of a slender body in an otherwise uniform flow of the velocity v is small compared to v, and to the sound velocity, a, in the undisturbed flow and also to the velocity difference $a - v$. Studying the validity of this assumption, Tsien distinguishes the ranges given in the following table, where "small" or "large" means that the perturbation velocity is "small" or "large" with respect to the indicated velocities. (Ref. 2)

Table I

	a	v	a - v
subsonic flow	small	small	small
transonic flow	small	small	large
supersonic flow	small	small	small
hypersonic flow	large	small	small

Thus especially in a wind tunnel for "high" Mach numbers, the sound velocity becomes small due to the low free flow temperatures and the perturbation velocity attains the same or a higher order of magnitude. This condition will actually be reached for different bodies at different Mach numbers. It was further shown by Tsien that the free flow Mach number, M, in relation to a certain body in the flow becomes "hypersonic" if the following expression holds true:

$$M \frac{d}{b} \approx 1$$

where d/b is the thickness ratio of the body; e.g., the flow field is "hypersonic" for an airfoil of 10% thickness ratio if $M \gtrsim 10$.

H. S. Tsien gives similarity laws for two-dimensional and axially symmetric "hypersonic" flows of this type in Refs. 1 and 2. This work is extended by W. D. Hayes in Ref. 3.

It has been shown already by Th. von Kármán (Ref. 4) that for hypersonic flow over a slender body the variation of fluid velocity due to the presence of the body is limited within a narrow region close to the body which is termed by H. S. Tsien the "hypersonic boundary layer".

It is to be noted with respect to the above definitions:

a) The fluid is regarded as a continuum.
b) The change of the physical picture of the flow field from "supersonic" to "hypersonic" (Table 1) does not seem to be of any fundamental nature. The distinction was rather brought about by the need for an extended mathematical treatment.

3. W. F. Hilton (Ref. 5) distinguishes customarily between low speed, subsonic, transonic and supersonic "speeds". He contemplated a further increase in speed, especially at higher altitudes and thus attains a "hypersonic" regime. These "hypersonic" speeds are defined as speeds so high that the time of passage of a given wing or body past a given fixed point in space is smaller than the average time elapsing between successive collisions of air molecules. Thus after an air molecule impinges on the body and rebounds, it will be unlikely to collide with another air molecule until after the body has passed by. In a treatment of a body moving in this regime only those molecules which strike the body need be considered, since energy sharing collisions happening behind the body can have no effect on the body itself.

Hilton defines on this basis a dimensionless number, "N", separating the supersonic from the hypersonic regime if its value is unity:

$$N = \frac{\nu \lambda}{c \bar{v}}$$

smaller where λ = mean free path, c = chord of wing or length of body, $\bar{v}$ = molecular velocity.

As to the flow disturbed by the body, it can be said that the shock wave is leaning back very nearly parallel with the flow. Therefore, a shock wave of normal thickness t, if set at a Mach angle μ will have a thickness in the direction of motion of

$$\frac{t}{\sin \mu} = Mt$$

The above conditions occur if the chord is small, the Mach number is high, and the shock wave thickness is large. The latter condition can be met by decreasing the density.

4. The following terminology was in use at the Kochel Institute. All Mach numbers above 6 were termed "Superschall" (Schall = sound) with respect to M ≤ 6 "Ueberschall" (Supersonic). This terminology was not based on theoretical reasoning. Rather, it described a range of wind tunnel Mach numbers which could not be attained in the Kochel 40 x 40 cm tunnels ($M_{max} \sim 6$). For obtaining Mach numbers larger than 6 special facilities had to be erected. (See e.g. Ref. 6).

5. The field of fluid mechanics where the mean free path of the molecules attains values which come into the order of magnitude or exceed the boundary layer thickness or body dimensions was termed by H. S. Tsien "superaerodynamics". (Ref. 7, compare also the work of E. Saenger)

6. (It should be noted here that the expression "hypersonic" is a term which has been applied for many years already to a certain range of extremely high frequencies in the field of ultrasonics.)

7. To draw some conclusions from the above, it is possible to relate the different regimes, which have been termed "hypersonic" to a tentative overall picture of the "realms of fluid mechanics" as given by H. S. Tsien. (Ref. 7) Here the ratio of Mach to Reynolds number is taken as a descriptive parameter which retains its physical significance also in regimes where the concepts of M and Re individually lose their applicability. Several "realms" are singled out for the purpose of applying different theoretical treatments by introducing tentative boundaries which are given by certain values of the ratio of mean free path to the thickness of the boundary layer on a body, λ/δ.

Table II

a) $\lambda/\delta \lesssim 10^{-2}$ Realm of "conventional gas dynamics" in a continuous medium.

b) $10^{-2} \lesssim \frac{\lambda}{\delta} \lesssim 1$ Realm of "slip flow"

c) $1 \lesssim \lambda/\delta \lesssim 10$ Realm where collisions between molecules and collisions of molecules with the surface of a body are equally important.

d) $10 \lesssim \lambda/\delta$ Realm of "free molecule flow"

Tsien's definition of "hypersonic" deals with the realm a). For example, if a range of Reynolds numbers around 10^6 and larger and high Mach numbers occur then the Mach numbers become hypersonic at different values depending on the different thickness ratios of bodies.

Hilton's definition of "hypersonic" separates roughly if the value of his "number" is unity the range d) from the others. For example if extremely low Reynolds numbers and high Mach numbers occur, then the latter become "hypersonic" depending on the length of chord or body.

This definition somewhat duplicates the expression "superaerodynamics" given in 5).

8. It is also of interest for practical purposes to compare the two definitions in view of the wind tunnel type which simulates the free flight conditions.

Table III

H. S. Tsien's Definition of "Hypersonic"

Free Flight	Wind Tunnel
"Medium" altitudes, (say up to about 60-80 km), depending on the size of the missile, High speeds.	High Reynolds numbers, therefore high test section densities with negligible mean free path. High Mach numbers. Requires high supply pressures and temperatures.

Table IV

W. F. Hilton's Definition of "Hypersonic"

"High" altitudes, (say above 60-80 km) depending on the size of the missile. High speeds.	Extremely low Reynolds numbers, therefore low test section densities with a mean free path comparable to test section dimensions. High vacuum technique. Molecular beams.

9. The NOL hypersonic wind tunnel is intended for research in range a) of 7) and is thus of the type described in Table 3. It might be possible later, however, to attain also conditions which correspond to range b) of 7). At present "hypersonic" is used at NOL to cover "high Mach numbers not presently attained in supersonic wind tunnels". In connection with models and depending on their thickness ratio the flow field will be hypersonic according to the definition of H.S.Tsien.

Typical approximate numerical example for the NOL hypersonic wind tunnel:

$p_0 = 50$ atm
$T_0 = 800\ ^{\circ}K$
model length $= 30$ cm
thickness ratio $\frac{\delta}{\ell} = 0.1$
$M = 10$
$Re = 10^6$
$\lambda/\delta = 10^{-2}$

From these figures it can be seen:

a) With $\lambda/\delta \sim 10^{-2}$ the air in the test section can be regarded as a continuous medium.
b) With Re = 10^6 the drag due to friction will be above its critical value.
c) With the thickness ratio 0.1 and M = 10 the flow field will be hypersonic following Tsien.

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